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A Study of Frequencies for Communication Services in the Mars Region

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1.0 Introduction

UHF is the frequency recommended in the current CCSDS proximity link standard and it is also the frequency of choice for past, current and planned Mars missions. However, other frequencies have also been used or considered by other missions. Which frequency band should be used for Mars local links? Should there be one frequency or multiple frequencies? There are many factors affecting the answers to these questions. This paper examines various factors affecting the choice of the local link frequency, including link performance, propagation effects, and regulatory issues.

2.0 Frequency Bands of Interests

The frequency bands of interests are UHF, S, X, and Ka-band. Recent Mars lander or rover missions have employed UHF. The specific UHF frequency of interest is approximately 420 +/- 30 MHz. S-band (with 10 MHz for transmit and 10 MHz for receive, centered at 2115 and 2295 MHz respectively) has been suggested as a possible alternative to UHF. It is relatively close to UHF, but the shorter wavelength makes it more suitable for certain applications. X-band (two 50-MHz allocations, one in the 7.2 GHz band and the other in the 8.4 GHz band) is of interest because it is the frequency used by most existing and planned deep space missions for the links between spacecraft and the Earth. Ka-band (32 GHz) is attractive because it is a new DSN capability and it can support multi-megabit links.

There is also an allocation for deep space communication in the 37- 38 GHz band, which is being considered for use in human exploration of Mars. Possible use of this band for the Mars local links will be examined in the future when plans for human exploration become more definite.

3.0 Mission Scenarios

Mission scenarios play an important role in selecting the frequency for Mars local links. There are numerous mission scenarios for future Mars exploration. Many include local links. The types of local links that may be used are surface links (lander to rover), surface (including aerobots) to low orbiters, surface to areostationary orbiters, orbiter to orbiter and entry, descent and landing (EDL) links. They each have different mass,

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power and volume constraints. This section will discuss some of the options and what they mean in terms of choosing a frequency band for the local links.

3.1 Surface Links

The Mars Pathfinder lander to rover link is an example of this type of link. Pathfinder used a 459.7 MHz modem for two-way communications at 9600 bps. Both elements used simple whip antennas. The transmit power was 100 mW. Typically these links are line of sight and very short range (< 1 km). A problem for these links is blockage and multipath fading from the surface and rocks. The antennas are relatively close to the ground, which makes the fading problem worse. Generally, a shorter wavelength will provide better multipath performance but not enough to overcome the difference in free space loss.

These links typically employ a fixed broad-beam antenna. The desired antenna pattern is along the surface. Pathfinder used choked monopoles on the lander and rover. The mass of the UHF radio in the rover was about 100g and the dc power about 2W. A large lander will typically be able to support a larger mass and higher dc power than a small rover, but both mass and power are design constraints. A recent Mars 03 design with a surface link between the rover and lander used French S-Band radios (800g), with choked dipoles and 1W transmitters. The nominal data rate in both directions for that design was 256 kbps. The most recent Mars 03 rover design, however, will use UHF for in-situ communications (with a low-altitude orbiter) and X-band for direct to Earth links.

Generally these links, because of the short range, can be designed with large link margins for relatively high data rates and full duplex communications. Typically a shorter wavelength performs better in terms of multipath and the choice of S-Band over UHF makes sense for the surface links. Because of the smaller wavelength, S-band also has an advantage over UHF when there are severe mass and volume limitations. However, for links severely limited by power, UHF may be more preferable than S-band. X and Ka-band are not as suitable as UHF and S-band because of the much higher space loss.

3.2 Surface to Low Orbiter Links

For these links there are many types of surface elements. They can be large, capable landers or rovers, small short-lived probes, long duration small probes and aerobots – planes or balloons. The latter elements are not on the surface but they exhibit similar characteristics in terms of in-situ communications. For these links, the desire is to have antenna beams (of the surface elements) that are pointed up as opposed to the surface links where the antenna beams should be along the surface.

For comparison sake and without loss of generality, it is assumed that the surface element is communicating with a polar orbiter at an altitude of 400 km, like Mars'01. (The Mars Telesat program was looking at placing orbiters at an altitude of 800 km in near polar and equatorial orbits.) One of the factors that can significantly affect the choice of frequency for these links is the type of antenna carried by the surface elements and the orbiter. Based on previous designs, it is anticipated that surface elements will not use a steerable antenna for these links. It is also expected that a relay orbiter will have a nadir oriented, body-fixed low gain antenna (LGA), at least in the near-term. In the future, an orbiter may carry a steerable spotbeam antenna when it is operationally practical.

Elements talking to a polar orbiter will get 2 to 3 daylight passes/sol. Surface elements at higher latitudes (> 65 degrees) will see the orbiter a little more frequently. The pass duration is typically about 10 minutes (15 degree elevation cutoff) when the orbiter flies directly overhead. The duration is less when the orbiter is off to the side. The slant range to the orbiter changes rapidly during the pass as a function of elevation angle. The slant range at an elevation angle of 15 degrees is 1031 km and reduces to 400 km when the orbiter is directly overhead. The data rate capability can increase by almost an order of magnitude due to the change in space loss. Different data rate strategies can be played to maximize the data return. These may include waiting for a higher elevation angle (detecting a minimum SNR in the receiver) or switching data rates during the pass. This requires acquiring bit sync and code sync again but may lead to a larger returned data volume.

The following paragraphs will discuss the application of frequency bands for different types of landed elements and under both orbiter antenna scenarios. First, let's assume that the orbiter will carry a LGA.

3.2.1 Large Lander or Rover

These elements typically are not as constrained as some others in terms of power, mass and volume. They also tend to have higher data return requirements. They can support a higher transmit power because they will have solar arrays. (That may limit them to daytime-only communications.) UHF is better for this type of link than the other frequencies. Although UHF components are larger and heavier, it is more than offset by the benefit of a much smaller space loss. In addition, the larger lander and rover are also tolerant to the mass and volume penalties.

Using a 10W RF power amp in the transceiver will require about 50W dc. A higher mass allowance will allow these elements to fly a larger, circularly polarized antenna like a patch or helix rather than a whip. The helix pattern could be shaped to provide slightly more gain off to the sides than at zenith to compensate somewhat for the slant range difference. This can be done on the orbiter as well. The larger vehicle allows for carrying the mass of a duplexer for full duplex communications.

3.2.2 Small Probes

These elements' (e.g. DS2) mass, volume and power requirements are much more critical than for the large lander/rover. Power is generally from a battery or radioisotope heating unit (RHU). Transmission at night is probable because the Sun is not required for power. Typically, the output power is going to be less than 1 watt RF. DS2's output power was about 500 mW. Again, UHF is more suitable for this type of link. Generally for the small probes, the use of a UHF patch antenna is not feasible because there is not enough surface area for the ground plane and the mass is too large. The whip is a low mass, simple solution albeit with limited performance. The whip has a null overhead but the satellite rarely gets that high in elevation. The mass for the transceiver and antenna should be under 100g. The links are typically half-duplex because the mass of a duplexer is too high. The transceivers may employ a transmit/receive switch for two-way communications. These elements may include a real receiver (FSK) for commands or simply turn on their transmitter after receiving a beacon tone from the orbiter.

3.2.3 Aerobots

Balloons and airplanes, like the small probes, are typically very power limited because of the absence of large solar arrays. The mission duration can be from minutes for an airplane to days or weeks for a balloon. Video data from a short lived airplane will require very high data rates. If the plane is transmitting to an orbiter, it will be necessary to schedule the flight for an overpass by the satellite. Some airplane options would return data to a surface lander for relay to the Earth. There could be possible fading or blockage problems but the range would be much shorter than communicating with a satellite.

These elements are also very mass limited. Simple whip antennas are generally assumed. An airplane could try to use some type of conformal antenna (patch) if the structure is large enough. Again, the desired antenna beam direction is up but with a very wide beamwidth to cover the orbiter's trajectory and the preferred frequency is UHF when communicating with a satellite due to the smaller space loss. The transceiver mass should be as small as possible, like the small probes. These elements are generally battery powered or with small solar panels to recharge the batteries so dc power for transmission is at a premium.

The previous paragraphs assumed a LGA for the orbiter. Although this is a likely scenario for near-term missions, it may be possible for future missions to employ a steerable antenna. This will open the door for higher frequency bands.

3.3 Surface to Areostationary Links

For these links, the range is much larger. The altitude of an areostationary orbiter is about 17000 km. The slant range does not change much as a function of elevation angle because of the high altitude. The desired antenna coverage is looking up, but now the satellite is stationary. This allows for using much higher gain antennas on the surface elements. The antennas have to be pointed, but only once up at the satellite, as long as the surface element or satellite does not move. Use of a higher gain antenna implies going up in frequency to keep the mass and volume reasonable. S or X-band would be the preferred frequencies for links that use a high gain antenna (HGA). There is concern about interference between the local links and the direct to Earth (DTE) links. This will be addressed later.

Non-steerable antennas with moderate gain can be used in the surface element. This assumes that the surface element does not land on a steep slope and that the areostationary satellite is not close to the horizon. The link will support a lower data rate but still one that is reasonable, especially considering that the satellite will always be in view. The satellite will probably have both a high gain steerable antenna that has a spot beam on the surface, to support high data rates, and a medium gain antenna (MGA) that covers the entire disk of Mars plus low altitude orbiters. The MGA could support lower data rate return links as well as forward links.

Mass, power and volume concerns are the same as for the surface elements communicating with the low orbiters. Taking advantage of higher gain antennas, the transmit power can be kept to a reasonable level, i.e., a few watts, depending on the required data rate.

3.4 Cross-Links

Cross-links between orbiters at Mars could be for data relay, timing information, navigation or radio science. Their use is highly dependent on the orbiter constellation design. There are several possibilities for cross-links: those between orbiters at similar altitudes in a constellation, those between low orbiters and an areostationary orbiter and those between an incoming satellite and an orbiting satellite at Mars. This last option is for navigation purposes.

Cross-links between orbiters in a constellation will require antenna patterns that are omni in azimuth and above the surface of the planet. (This assumes the orbiters are at the same altitude.) They may just use a nadir pointed toroidal pattern antenna. If the antenna has an antenna for surface to orbiter links, it is possible that the same nadir pointed relay antenna could be used for cross-links but the performance would be relatively poor. If the cross-link is for low rate data or a beacon, that may be sufficient. The mass and power requirements for an orbiter are typically less stringent than for a lander because of the extra mass required to land a spacecraft on the surface – parachutes, retro rockets, air bags, etc. The link frequency chosen for this link is dependent on the antennas used on both orbiters. If the in situ relay equipment is used, UHF is the preferred frequency. If separate antennas are used with DTE radio equipment, than X-Band is preferred. If the primary usage of the link is for radio science than the link frequency will be defined by their requirements.

Cross-links from a low orbiter to an areostationary satellite will be similar to surface elements communicating to the areostationary satellite. The low orbiter will be moving across the planet relative to the high orbiter. The low orbiter will need an antenna pattern that will cover up to180 degrees, depending on the percentage of its orbit it wants to communicate with the areostationary satellite. This is the same as an antenna that would be pointed at the Earth. If a steerable antenna is used on the low orbiter it will have to track the areostationary satellite through this wide range. A hemi-spherical antenna could be used with low gain. If the spacecraft will only communicate for a short duration during an orbit then the requirements for the antenna can be relaxed.

Mass and power constraints are similar to the previous example. These links may use radio equipment that could be used for communicating directly to Earth. This assumes that the frequencies chosen are compatible. Most studies about an areostationary satellite at Mars have assumed X-Band for high rate links and UHF for low rate links. Perhaps all forward links would be at UHF to avoid the potential interference problem with commands sent from the Earth at X-Band.

A cross-link between an incoming satellite and an orbiting satellite would be done using the two satellites' DTE radio equipment with either a HGA on both spacecraft or one HGA and a MGA. Either way the spacecraft would have to point their antennas at each other. The link would presumably be at X-Band, the nominal DTE link frequency. The primary purpose for this link is to support approaching spacecraft navigation. The link would work out to a range of 2 to 10 million kilometers (5 to 10 days), depending upon the radio hardware and antenna gain. One of the spacecraft, presumably the one at Mars, would have to have the reverse transponding ratio. The transmission would be carrier only and could be one or two-way. One of the spacecraft would have to have a Doppler extractor – beat the Doppler signal against a local reference, digitize and telemeter the data to Earth.

3.5 Entry Descent and Landing

Using the in situ communications equipment for EDL is problematic if the communications is back to Earth. If the relay link frequency is UHF, there are limited large UHF receiving antennas. Depending on the spacecraft design, the relay antennas may be covered by a backshell. If the spacecraft is carrying X-Band or Ka-Band DTE radio equipment, EDL communications to Earth at those frequencies, through the DSN, is the best option.

Using the relay communications equipment for EDL is preferable when the Earth is out of view of the spacecraft. Transmitting EDL information to a low orbiter overhead or to an areostationary satellite is feasible. The biggest requirement is having an antenna that will be outside the shroud of the spacecraft and be able to see a satellite overhead. Getting visibility to a low orbiter could be a problem because of scheduling the overflight and the short duration of EDL. Communicating to an areostationary satellite provides better visibility but at a longer range. The EDL communications may use semaphores or a carrier signal instead of relatively high data rates. Of course an areostationary satellite would have to be positioned over the EDL site. If the landing element has in situ relay equipment on it, it could transmit through a switch to an external EDL antenna on the spacecraft backshell or other structure. The other option is to fly a separate EDL radio package that would be thrown away with the backshell. The package would include a battery for the short duration of EDL communications.

The antenna coverage for EDL will require a wide beam, low gain pattern. The spacecraft will not have any capability to point an antenna and the angles it has to communicate through will vary widely. The mass and power will have to be low, especially if the EDL radio equipment is an add-on to the regular spacecraft. Spacecraft power will be off of a battery so it should be kept to a minimum. A low orbiter would need an antenna with a relatively wide beamwidth to cover the trajectory of the incoming spacecraft. An areostationary satellite's antenna would want to cover the disk of Mars.

3.6 Mars Ascent Vehicle Communications

One of the Mars sample return mission concepts that has been explored would work as follows: A Mars Ascent Vehicle (MAV) will launch a small canister containing samples into Mars orbit. An orbiter will be launched from Earth to retrieve the canister in Mars orbit and return it to Earth. The mission operators on Earth need to know if the MAV has successfully launched the canister into Mars orbit. One method is to equip the MAV with a low power transmitter capable of sending a beacon or semaphore through a low gain antenna. The signal can be picked up by a nearby relay orbiter. UHF is most suitable for this type of application.

4.0 Telecom Hardware Technology

New terrestrial wireless technologies may affect the choice of frequency band for local links at Mars in the future. The relay links may be able to use some of this new hardware. The concern is whether the hardware is or can become space qualified.

Previous Mars missions have used UHF band communications. Viking used an UHF relay system between the landers and the orbiters. Pathfinder used a space qualified

Motorola UHF modem. MGS carries the French Mars Balloon Relay (MBR) UHF radio. DS2 carried an UHF radio to talk to the MBR. The two Mars 98 missions (lander and orbiter) carried Cincinnati Electronics UHF radios to communicate with each other. The focus for near term Mars missions has also been at UHF – Mars'01 orbiter. But S-Band has also been considered for the original Mars'03 rover communications. That link was designed to use the French SOREP S-Band transceiver for a surface link between the rover and the lander. The new Mars'03 rover mission will use UHF radios to talk to the Mars'01 orbiter. The Muses CN relay link is at L-Band. It takes advantage of commercial parts designed for the Personal Communications Services (PCS) band.

The major building blocks in a relay communications system are the transceivers (transponders), duplexer (if used) and the antennas. The major new bands of commercial interest are in the cellular phone bands (900 MHz and 1.9 GHz) and wireless LANs (Bluetooth, ISM) at 2.4 GHz.

4.1 Transceivers

The differences in transceivers at different frequency bands are really in the front end electronics. The back end processing, after IF sampling is really the same for different frequency bands. Higher frequency bands require accommodation of a larger Doppler offset and Doppler rate. There are complete transceivers on a chip that are commercially available and are very low mass and very low power (5 – 20 mW, 0.3 to 19.2 kbps). They use on-off keying and are very inefficient in terms of link performance. They are used for very short range communications. The required E_b/N_0 is 35 to 50 dB compared to 10.5 dB for an uncoded BPSK system (BER = $1*10^{-06}$).

In the front end, the specification for the oscillators has to be tighter at higher frequencies to achieve similar phase noise characteristics. There will be more options available in the commercial frequencies for LNAs, mixers and narrowband filters (SAW) on the receive side and power amplifiers on the transmit side. There is sufficient availability of parts at UHF as evidenced by the hardware that has already been built but there is more choice at the commercial bands.

While the availability of parts is greater at 900 MHz, 1.9 GHZ and 2.4 GHz, these parts may not match the requirements for the local links. Many of the services these parts are designed for are narrowband (cellular 9.6 - 19.2 kbps). The other concern is reliability over radiation and temperature. Most Mars missions are relatively low radiation (<20 krads) but this can still eliminate many parts from consideration. Temperature effects can be more critical unless the mission is very short. The Muses CN rover is using commercial parts that work over a temperature range of –100 to +100C.

There is not a large difference in performance for power amplifier chips and LNAs between UHF and S-Band. Typically the UHF chips have better power efficiency.

4.2 Duplexers

With increasing frequency the mass of the duplexers should decrease. The mass for the UHF duplexer on Mars'01 is 161g. Insertion loss is about 0.8 dB for both transmit and receive. PCS phones have very small duplexers - about 3 by 8 cm but the insertion loss is 3 – 4 dB. At S-Band it is expected that the mass will decrease, below 100g with similar performance as at UHF.

4.3 Antennas

The biggest change to the relay communications hardware with regard to the frequency band is to the antennas. At UHF, the most prevalent types are a simple whip, a patch or a helix. Reflectors or horns are not an option. At S-Band, small commercial patches are readily available. At X-Band we can start to consider small reflectors or horns along with patches.

UHF: Pathfinder flew a choked monopole on both the rover and lander. The antenna length was about 45 cm and the maximum gain was 1.4 dBi. The Mars 98 orbiter and lander both flew UHF quadrifilar helix antennas from Litton. The mass was over 1 kg and the peak gain was 3 dBi. The 3 dB beamwidth was about 120 degrees. Newer versions of this antenna have a reduced mass of about 0.5 kg.

JPL has developed some breadboard UHF patch antennas. One antenna provided a CP signal with a 7 dBi gain, a 60 degree 3 dB beamwidth and a bandwidth of 40 MHz. The conducting patch was 32 x 32 cm, 2.5 cm above a 38 x 38cm ground plane. It had an overall thickness of 2.8 cm. The estimated mass was 0.5 kg. The beamwidth is not very broad. A higher dielectric-constant material could be used to shrink the antenna and broaden the beam and reduce the gain. This will increase the antenna mass and reduce the bandwidth.

Another option is a crossed-slot patch integrated into a solar array. Using a high dielectric substrate, the size is 25 x 25cm. The mass is 1.3kg and the peak gain is 4.5 dBi. Using a lower dielectric substrate increases the size to 33 x 33cm but the mass goes down to 0.5kg. Peak gain is 5.0 dBi.

S-Band: Antennas at S-Band can be the same type as at UHF – monopole, patch and helix. At this frequency we can take advantage of small commercial patch antennas for links that require little gain. Toko has a vertically polarized S-Band patch for wireless LAN applications. It has a peak gain of 0 dBi at zenith and a gain of –4 dBi along the azimuth. It should be mounted on a ground plane with size 50 x 76 mm. The center frequency is 2450 and the bandwidth is +/- 50 MHz.

The size and mass of monopole or helix antennas is reduced compared to UHF but the gain and beamwidth remain the same.

X-Band: At X-Band we can start to use small reflector antennas or horns for links to an areostationary satellite and as a backup for an Earth link. The Pathfinder antenna was a microstrip dipole array. The mass was 1.2 kg with a peak gain at 8.4 GHz of 24.8 dBi.

Another option is a horn. Stardust flew an X-Band horn with a gain of 22 dBi at 8.4 GHz. The aperture size was 20cm and the mass was 0.65 kg.

5.0 Link Performance and Design Considerations

Section 3 examined various mission scenarios. This section will discuss the relative link performance for those scenarios using different frequencies.

5.1 Surface Links

For surface links, the range is so short that space loss is not as critical in determining link performance. Generally, with a small output power and a whip or other low gain antenna, the links have large margins. The margins are sufficient to offset multipath fading losses. Choice of frequency for these links is influenced by factors other than link performance, like mass, volume and available equipment. Of the frequencies considered, UHF and S-band are more suitable than X- and Ka-band. If the surface elements are severely energy-limited or if the required power for these links are relatively high, then UHF would have an edge over S-band. Mars Pathfinder chose UHF because of an existing radio that it could use - a simplex UHF radio with a 100 mW transmitter. A recent Mars lander/rover study considered using S-Band because the antenna mass was small and they could use an existing French S-Band transceiver. The lower mass at S-Band also allowed for adding an S-Band duplexer for full duplex communications.

5.2 Links between Surface Elements and Low-altitude Orbiters

For links between surface elements and low orbiters, choice of link frequency affects link performance greatly. The higher frequencies allow for smaller mass and volume but the power requirements increase considerably. This is true if neither the surface transmitter nor the orbiting receiver have steerable high gain antennas, but instead have fixed low gain antennas.

Table 1 shows a comparison between UHF, S-Band and X-Band for a return link at 16 kbps to an orbiter. The same antenna gain was assumed for both the transmit and receive antennas at each frequency. Note the difference in power level required between the frequency bands to achieve a 3 dB margin. This is all due to the difference in space loss. This is why UHF is so attractive for links where there are no steerable antennas.

When steerable high gain antennas are assumed for either the receiver or transmitter, the advantages of UHF disappear. The advantages of the higher frequencies then come into play – lower mass and smaller volume for the surface elements.

For landed elements at Mars, communicating to a low orbiter, UHF is the most viable option when non-steerable antennas are employed on both ends of the link. S or X-Band could be applicable when the link is from a much smaller body like an asteroid (Muses CN) or a comet (ST4 Champollion) where the range is much less.

If a steerable antenna is used in the link, most likely on the orbiter, then a move up in frequency to S or X-Band is desirable. Moving up to a higher frequency band would benefit the surface elements in several ways. First, it would alleviate the mass and volume constraints. The biggest change is the size and mass of the antenna on the surface element. Secondly, it would allow the surface elements to take advantage of the greater availability of (COTS) hardware developed for terrestrial (S-band) wireless systems. The orbiter antenna would only need a gain of 16.5 dBi at S-Band to match the performance at UHF as shown in Table 1. This gain could be achieved using multiple patches or an array of helices.

It should be pointed out that moving up to a higher frequency than UHF also would result in a smaller satellite footprint, which has both advantages and disadvantages. A smaller satellite footprint would reduce the potential for interference and increase frequency reuse capability. On the other hand, a smaller footprint would make it difficult for the satellite to provide simultaneous coverage to a wider surface area, if and when it is needed.

5.3 Links between Surface Elements and An Areostationary Satellite

For links between surface elements and an areostationary satellite, use of higher frequencies than UHF make the most sense. Studies of an areostationary satellite at Mars have generally assumed that the relay links will be X-Band up and down. Both ends of the link would have steerable reflector antennas and return link data rates up to 1 Mbps could be supported. The transmit power from the surface would only be about 2W RF with a 0.3m antenna (EIRP of 57 dBm).

The problem with this scenario is potential interference between the X-Band uplink from the Earth to the satellite and the X-Band forward link from the satellite to the surface element. Both links would be at 7.2 GHz. (The satellite downlink to Earth would be at Ka-band in order not to interfere with the 8.4 GHz return link from the surface to the satellite.) Solutions for the interference problem include the following: time sharing the Earth uplink with the surface element forward link, using S-band or Ka-band for the uplink from Earth to the satellite, or using S-Band or UHF for the forward link from the satellite to the surface element. A 2 kbps UHF forward link could be supported using a UHF MGA (large helix) and a 10W transmitter. (It should be noted that future use of S-band for uplinking from DSN is constrained by the emerging, world-wide, third-generation terrestrial wireless systems, IMT2000. Part of the spectrum allocated for and employed by IMT2000 includes the DSN S-band uplink spectrum. Potential interference may limit DSN's ability to continue to use S-band freely in the future. It should also be noted that Ka-band for uplink telecommand is not in the current DSN plan.)

The problem with using UHF for the forward link is that it requires the surface elements to have equipment at two different frequencies. If that element is also going to communicate with a low orbiter at UHF anyway, then the equipment is already part of the surface element communications subsystem. If UHF is used, it allows the areostationary satellite to use a MGA to close the forward and return links (2 to 8 kbps) with surface elements and low-altitude orbiters equipped with a LGA. The UHF antenna will have a global beam which will cover the entire Mars disk and low-altitude orbiters and will make operations simple. In addition, it allows the areostationary satellite to provide redundant relay links to surface elements that have been equipped with a UHF package for communications with low altitude orbiters.

Table 2 examines some of the links to and from an areostationary satellite. The table shows that low rate forward and return links can be supported at UHF and that with a relatively small antenna (0.3m) on the surface element, return rates up to 1 Mbps can be supported at X-Band.

5.4 Orbiter-to-Orbiter links

For orbiter-to-orbiter links, the choice of frequency band is dependent on what data is being transmitted. Timing or navigation signals between elements in a constellation could be done at any frequency, but would use equipment already on the spacecraft, most likely UHF. The links will either use the existing nadir oriented LGAs or separate LGAs looking off to the side.

High rate data transfer between elements is most likely to occur between a low orbiter and an areostationary satellite to take advantage of the latter's greater DTE link capability. This link would use the low orbiter's DTE link capability at X-Band to communicate to the areostationary satellite.

An orbiter-to-orbiter cross-link with an approaching spacecraft can be used to improve navigation accuracy. Communications with an approaching spacecraft would start about 5 to 10 days prior to arrival, when the communications range is 2 to 10 million kilometers. The large communications distance makes it necessary to use a higher frequency than UHF. Since current and planned deep-space missions all use X-band for direct-to-earth communications, X-band is the frequency of choice for this application.

Radioscience may use an X-band cross-link to measure the characteristics of the atmosphere using occultation techniques.

5.5 Entry, Descent and Landing Communications

If EDL communications is to a Mars orbiter, it should be done at UHF. The incoming satellite will not be able to point an antenna. Whether it communicates to a low orbiter flying overhead or to an areostationary satellite, it can close a low rate link or simple semaphores at UHF. Using S-Band or X-Band does not appear to be feasible because of the much larger space loss. A low orbiter with a steerable antenna, trying to track the spacecraft, would not be practical because of the velocity of the incoming spacecraft and the uncertainty in the spacecraft's position.

6.0 Propagation Effects

The environment of Mars is significantly different from Earth's in many aspects, from its surface to its outer ionosphere. Its effects on radio wave propagation may also be different. How does Mars' environment affect RF wave propagation? Does it affect the selection of the communications frequency? These questions will be addressed briefly below.

6.1 Martian Ionospheric Effects

The Martian ionosphere is a single ionized gas layer with relatively low plasma density. It only has effects on low frequency waves below 450 MHz and is almost transparent for high frequency bands (S, X and Ka). It has a loss of ~0.5 dB for the VHF (including UHF) band and negligible losses for higher frequency bands. The Martian ionosphere may be used as a reflector for future Mars ground-to-ground communication. The ionosphere has a critical frequency of ~4 MHz for vertical incidence. A wave with a 90 degree incidence angle and with frequency higher than the critical frequency will pass through the ionosphere unattenuated. The ionosphere can be used for future Mars surface trans-horizon communication.

6.2 Martian Atmospheric Effects

The Martian atmosphere (or troposphere) is very thin and it is expected to have very little effect on radio wave propagation. Because Mars has very low atmospheric pressure (less than 1% of Earth's), the Martian atmospheric radio refractivity is about two orders of magnitude smaller than that of Earth. Lower frequencies (UHF band) are expected to have very little refractive and scattering effects in the Martian troposphere. High frequency wave (above 1 GHz) may be bent or trapped by the vertical refractivity gradient when the wave incident angle is very close to the horizon.

6.3 Martian Cloud Effects on Wave Propagation

Optical depth is a measure of propagation loss. A transparent object has a small optical depth while an opaque object has a large optical depth (>>1). The optical depths of Martian clouds and fogs are about 1.0 at visual wavelengths. Thus, it is expected that they have little attenuation for microwave and light-wave propagation. In the limiting case, the Martian clouds are expected to be similar to terrestrial high-level cirrus clouds. Martian aerosols (haze) have also been found to have a small optical depth (less than 0.5). The total attenuation due to Martian clouds, fog and aerosols should be less than 0.3 dB at Ka-band. For lower frequency bands, the attenuation is almost negligible.

6.4 Martian Atmospheric Gaseous Attenuation

The atmospheric gaseous attenuation at Mars is worse at a higher frequency than a lower frequency. However, the worst case loss (at Ka-band) is still less than 1 dB. This is because the Martian atmosphere has very low concentrations of gaseous H_2O and O_2. Martian gaseous absorption is at least three orders of magnitude lower than that at Earth. An accurate water vapor altitude profile at Mars is not yet available. A conservative estimate for worst case Martian atmospheric absorption is an increase by a factor of 1.5.

6.5 Martian Background Noise Temperature

Radio noise emissions at Mars are mainly from its atmospheric emission and surface noise. Mars has lower surface temperatures, lower atmospheric absorption and radiation, but higher surface emissivity due to the roughness of soil and rocks. The actual radio noise contributing to the antenna temperature is strongly dependent on the antenna orientation, elevation angle, and gain pattern. For a downward looking antenna, the total noise temperature is about the same as the Earth's for all frequency bands of interest. For an upward looking antenna, the noise temperature is slightly below that at Earth (by 0.5 dB).

6.6 Martian Dust Storm Effects

Dust storms in Mars can significantly affect a communication link. A large dust storm can cause at least 3-dB loss at Ka-band. Lower frequency bands (UHF, S, and X bands) suffer less dust storm attenuation, which has a linear relationship with frequency. Most large storms occur in the southern hemisphere during later spring and early summer.

6.7 Communication Blackout during the Martian Atmospheric Entry Phase

When a high-speed spacecraft enters the Martian atmosphere, a plasma sheath is formed in the front of the spacecraft due to the impacting ionization. A 30-second communication disruption at X-band occurred during the Mars Pathfinder decent phase. If the frequency of a communications signal is higher than the surrounding plasma frequency, there will be no communication disruption. It is believed that this is the case at Ka-band.

6.8 Assessment of Overall Propagation Effects

The overall signal attenuation of a radio wave propagating in the Mars environment for various frequency bands are listed in the table below.

Because Mars has a thin atmosphere and few clouds, high frequency waves will not suffer losses as large as they experience on Earth for line of sight propagation. From propagation point of view and excluding free space loss, there is no significant difference for the four frequency bands of interests.

7.0 Spectrum Regulation and Test Considerations

Currently, no regulatory or spectrum organization claims to regulate the radio frequency spectrum on or in orbit at Mars. However, the regulatory regime at Earth affects the choice of frequencies used by missions for communications to and from Earth as well as for testing on or near the Earth.

Systems operating in the radio astronomy and passive services are particularly sensitive to interference; consequently, extremely low protection criteria have been established to protect these services. Of the bands of interest, only the UHF band has allocations to the radio astronomy service (406-410 MHz) that are directly in the band of interest. S-, X-, and Ka-bands have no radio astronomy service allocations at the specific frequencies under consideration for Mars (i.e., the deep space bands). While it is unlikely that operations at Mars will exceed the protection limits for the passive services, testing of systems at Earth will require careful planning especially at UHF.

8.0 Frequencies for Active Sensors

Various frequency bands will be needed for future active sensing activities in the Mars region, including synthetic aperture radar (SAR). The choice of frequency for active sensors is influenced by the intrinsic characteristics of each frequency band relative to the specific sensing activity. For example, one frequency may be more suitable for detecting subsurface water while another is more suitable for topographic mapping. The choice of frequency is also influenced by the available bandwidth, hardware availability, and technology maturity. While it is not the purpose of this paper to determine what frequency bands should be used for various sensing activities in the Mars region, the objective is to identify or project potential frequencies for these applications and to insure compatibility with the communications and navigation frequencies.

Table 3 gives the frequencies that have been either used by or proposed for active sensors operating in the Earth environment. While the Mars environment is different from the Earth's in many aspects, the operating frequencies for active sensors for future Mars missions, such as SAR, are likely to be influenced by what Earth sensors have been or will be using. As such, this table gives potential frequencies for sensors for future Mars missions. Of all the bands shown in the table, only the 430-440 MHz frequency overlaps with the UHF frequency being considered for communications and navigation. SAR sensors in the 430-440 MHz band typically use linear FM pulses with peak radiated power in the range of 6-1500W, 1000-2000 Hz pulse repetition rate, and

1-5% duty factor. Use of this frequency for a SAR mission in Mars can potentially interfere with the communications and navigation systems operating at UHF. While it may be premature and there may not be sufficient justifications to exclude this band from future SAR missions, it is prudent to incorporate this factor in the frequency plans, channelization schemes, and future frequency assignments for both local communications and science applications in the Mars region.

9.0 Other Factors Affecting Choice of Frequency

In addition to the various parameters discussed above, there are other factors that should be considered in selecting an operating frequency for in-situ communications and navigation.

9.1 Availability of Sufficient Bandwidth

Availability of sufficient bandwidth to meet near-term need and accommodate future growth is a must. For the purpose of this discussion, the various local links can be divided into two categories: high-rate links between elements with directive, steerable antennas at both ends of the links, and low-rate links between elements with non-steerable, fixed-beam, low-gain antennas at one or both ends of the links. Because of the distinct characteristics, the low-rate links will likely use a low carrier frequency and the high-rate link a higher frequency. Accordingly, bandwidth availability will be discussed along these lines.

A user study conducted earlier at JPL provided a rough estimate of the amount of bandwidth needed for each of these two types of links for three exploration eras: Mars Sample Return, Robotic Outpost and Human Exploration [1]. Results of that study indicate that a few megahertz of spectrum is sufficient for the low-rate links. The study considered only communications requirements. Ranging or other signaling techniques for time-of-arrival measurements, such as direct-sequence spread spectrum signaling, will certainly increase the amount of required spectrum. Although there are currently no explicit requirements for this type of measurement, one cannot rule it out for all future missions. From a spectrum planning point of view, it is necessary to provide sufficient spectrum so as not to preclude this type of measurement in the future.

For the high-rate links, the user study indicates that 10 MHz is sufficient for the first two eras and more than 50 MHz is needed for the Human Exploration Era. Again, these requirements are for communications only. Because of the relatively large bandwidth required, ranging or other signaling techniques for time-of-arrival measurements will not significantly increase the required bandwidth.

These bandwidth requirements were based on certain exploration scenarios, mission models, and communications infrastructure around Mars. All are under constant change. As such, these requirements cannot be viewed as hard requirements. They are at best rough-order-of-magnitude estimates and should be applied accordingly.

There is currently no regulation dictating the amount of spectrum in each band that can be used in the Mars region. From a spectrum allocation point of view, one should maximize, within reason, allocations to meet any foreseeable requirements. However, hardware, costs and other constraints can place a practical limit in some of these bands. It is important that these limits, if any, be considered in implementing a telecommunications infrastructure around Mars and in developing interoperability standards.

The achievable bandwidth of a low-gain, broad-beam antenna, which is likely to be used by many elements in the Mars region, can be a limiting factor at UHF. A patch type of low-gain antenna is generally very narrow band. A patch can typically achieve 2-3% bandwidth, and 6-8% is possible with increased thickness and size. At UHF, this translates to 12 and 35 MHz of available bandwidth that a single patch antenna can cover. With separate transmit and receive antennas and the added mass, volume and cost, the amount of bandwidth that a Mars element can cover increases to 24 and 70 MHz. The helix low-gain antenna can achieve a wider bandwidth, in the 10-15% range. At UHF, one helix antenna can cover 60 MHz. With separate transmit and receive antennas, the useable bandwidth would be increased to 120 MHz. There are design techniques to increase the bandwidth further at the expense of increased complexity, cost, volume, and mass.

Considering these practical constraints, UHF does not appear to have sufficient bandwidth to support high-rate links. It should, however, have sufficient bandwidth for the low-rate links. The bandwidth requirement for the low-rate data links is very moderate. Assuming 60 MHz of bandwidth and allowing 30 MHz separation between the transmit and receive sub-bands, there is still a total of 30 MHz of useable spectrum to support a mixture of simplex, half-duplex, and full-duplex low-rate links, with an imbedded ranging signal in some of these links.

Bandwidth aside, the high-rate links are likely to employ a higher frequency band than UHF due to link performance and hardware considerations. Of the bands of interest, S, X and Ka-band are all good candidates. Ka-band is more suitable than X-band for multi-megabit links.

9.2 Backward Compatibility

Backward compatibility is important for the near term. Near term lander/rover missions rely on and take advantage of existing orbiting assets to provide relay capability, because of the lack of a customized Mars telecommunications and navigation infrastructure. Of the frequency bands considered, UHF can allow new lander/rover missions to relay data with existing orbiting assets.

As the Mars infrastructure begins to take shape in the future, backward compatibility will be less of an issue. The infrastructure could begin with customized communications payloads piggy-backed on science orbiters or carriers. New capabilities and enhanced performance designed for future missions can be introduced to these payloads.

9.3 Emergency Backup from DSN

If the local link frequency of an in-situ element coincides with one of the DSN's operational frequencies (S, X, and Ka-bands), the DSN may be able to provide emergency backup to that element. The DSN already has both transmit and receive capabilities at S and X-bands, and Ka-band receive capability (plus a radioscience uplink) at some stations. However, X-band is better suited than other frequencies in terms of providing emergency backup because of the following reasons:

S-band had been extensively used by many missions in the past and continues to be the primary communications frequency for a few legacy missions. In terms of link performance, S-band is better suited for emergency communications than X and Ka-bands because of smaller space loss and less atmospheric effects. Additionally, S-band has the highest transmitter power at the largest antenna (70m) in the DSN, making it even more attractive as an emergency communications frequency. Unfortunately, the availability of S-band to future deep-space missions is constrained by IMT2000.

Ka-band is not as well suited as a frequency for an emergency backup as X-band. The DSN Ka-band uplink, if implemented, may not be as high power as X-band. The performance of a telecom link using a LGA on the spacecraft also favors X-band over Ka-band.

9.4 Sharing of DTE Hardware

If the in-situ element has both a direct link with the DSN and an in-situ link, using the same frequency for both links may make it possible to share or reuse the same communications hardware for both links. This could result in cost and mass savings. Of the four frequencies considered for local links at Mars, all except UHF can potentially enable hardware sharing. X-band however is more readily to achieve this than the other two frequencies. As previously stated, continuing usage of S-band in the future is hindered by IMT2000. Although Ka-band is being added to the network, it has yet to be flown as an operational frequency. All currently planned missions employ X-band for links with the DSN. Future missions having low data rates are likely to continue to use X-band. Only very high-rate missions are likely to be the first to migrate to Ka-band. Massive migration to Ka-band is not expected until the technology has been operationally proven. Until then, X-band is clearly the choice for this purpose.

9.5 In-Flight Testing of the In Situ Radio Hardware

An issue with flying the relay hardware is the ability to test it during the flight to Mars. There are a few issues: 1. Is testing the relay equipment required? 2. Is the relay antenna visible or is it covered up by spacecraft structure? 3. Is a waiver required for testing the specific frequency?

If the antenna is visible then it is reasonable to conduct a one or two-way test with ground equipment. At S or X-Band this is not a big concern because the relay frequencies will be in the deep space allocation. At UHF it is a problem for an uplink from Earth. Performing a test with an Earth uplink will require a waiver to operate out of band. The tests must be performed such that they do not interfere with overhead UHF satellites and there are limited ground stations with an UHF uplink capability. The DSN has no UHF capability, up or down. A one-way test from the spacecraft is feasible out to Mars range, depending on the relay antenna gain. Such tests were performed on the MGS MBR UHF system using the Stanford 46m radiotelescope. The received energy is so small that it does not interfere with ground or space UHF bands.

If the antenna is not visible during the Mars trajectory, the only option is to have some sort of self contained test in the radio. The radio could test itself and then telemeter test data back to Earth. No current equipment has such a feature.

Testability of the relay package is an important issue that must be addressed in the spacecraft design process.

10.0 Summary and Recommendation

The advantages of the four frequency bands of interest have been analyzed in general terms for various types of telecommunication links and for various criteria. It is clear that no one single frequency is good for every type of link and meets all evaluation criteria. It is also clear that not all factors affecting the choice of frequency are equally important and that the relative importance of these factors could vary as a function of time. Multiple frequencies will likely be needed in the Mars region at different times and for different applications. In light of this, it is necessary to adopt a flexible frequency allocation approach that will not be dependent on a specific exploration scenario, a specific architecture, or a specific multiple access scheme.

Considering the pros and cons of each frequency band, present exploration plans, and future exploration possibilities, it is envisioned that a single frequency will probably be sufficient for the very near-term, and additional frequency bands will be introduced to Mars as the communications network around Mars gets more complicated.

The near-term environment will probably have one or two relay links between one or more surface elements and one or more orbiters. Some surface elements will carry a package for direct links with the Earth. As more elements are put into the Mars region, either in orbit or on the surface, additional connectivity among surface elements, among orbiters, and between surface elements and orbiters will be required. New frequencies may be needed to enable new applications. The following is a possible frequency usage scenario.

UHF will be used initially by near-term missions for relay links with low altitude orbiters. It will continue in the future, as the primary frequency for relay links between landed elements and low altitude orbiters. These links will likely employ a LGA at both ends of the link, at least for the near-term. UHF will likely be used for all surface-to-surface links, except where severe mass and volume limitations necessitate use of S-band. UHF can also be used to facilitate the operations of a Mars Communications and Navigation Network, if and when it is implemented.

S-band can be introduced to the Mars region for surface-to-surface links when there is a severe limitation on mass and volume, or when there is sufficient power to close the link. It can also be used for surface-orbit links when flying a directive antenna on board the orbiter is technically and operationally practical. At this point, S-band can replace UHF as a primary frequency for all relay links between an orbiter and a landed element.

X-band can be used to support approaching spacecraft navigation and radio science when the opportunity arises. It can also be used to support links between a low altitude orbiter and a high altitude orbiter. However, its major use is to support high-rate relay links between a stationary satellite and a large landed element that can afford to use a directive antenna. Such use will not come until a relay satellite is placed in Mars areostationary orbit. When it does, X-band, augmented with UHF, will provide sufficient bandwidth and band diversity to support various links (surface-orbit, orbit-orbit, surface-surface, etc.) with a wide range of data rate capability.

Ka-band has a place at Mars when human exploration begins. It has ample bandwidth to support multi-megabit data rates expected for this era.

Reference:

[1] "Multiple Access and Frequency Plan for Mars Region Communications/Navigation: Peer Review of Work in Progress," JPL Internal document, dated March 7, 2000

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Mars Telemetry Link Budget

Mars Radius	**3398**	**km**
Orbit Altitude	**400**	**km**

Link Frequency		UHF	S-Band	X-Band
Elevation angle	**deg**	**20.0**	**20.0**	**20.0**
LANDER TX PARAMETERS				
Transmitter Power,	dBm	26.0	41.1	52.4
Transmitter Circuit Losses	dB	-1.0	-1.0	-1.0
Antenna Gain	dBi	0.0	0.0	0.0
Axial Ratio	dB	2.0	2.0	2.0
Modulation Index	deg	60.0	60.0	60.0
LINK PARAMETERS				
Range	km	894.3	894.3	894.3
Link Frequency	MHz	401.5	2292.0	8435.0
Atmospheric Attenuation	dB	0.0	0.0	0.0
Space Losses	dB	-143.5	-158.7	-170.0
ORBITER RX PARAMETERS				
Sky temperature	K	240.0	240.0	240.0
Pointing angle (Rel. to Nadir)	deg	57.2	57.2	57.2
Antenna Gain	dBi	1.0	1.0	1.0
Axial Ratio	dB	2.0	2.0	2.0
Polarization Losses	dB	-0.2	-0.2	-0.2
Receiver Feeder Losses	dB	-1.0	-1.0	-1.0
Receiver Noise Figure	dB	3.0	3.0	3.0
System Noise Temperature	K	550.9	550.9	550.9
Noise Spectral Density	dBm/Hz	-171.2	-171.2	-171.2
TOTAL POWER SUMMARY				
Received Power	dBm	-118.8	-118.8	-118.8
Received Pt/No	dB-Hz	52.4	52.4	52.4
SUPRESSED CARRIER - COSTAS LOOP				
Loop Bandwidth	Hz	200.0	200.0	200.0
Carrier Power/Total Power	dB	-6.0	-6.0	-6.0
Received Carrier Power	dBm	-124.8	-124.8	-124.8
	dB			
Carrier SNR in the Loop	dB	23.4	23.4	23.3
Required Carrier Loop SNR	dB	10.0	10.0	10.0
Loop SNR Margin	dB	13.4	13.4	13.3
DATA CHANNEL PERFORMANCES				
Data Symbol Rate	sps	32000	32000	32000
Data Bit Rate (1)	bps	16000	16000	16000
Data Power/Total Power	dB	-1.2	-1.2	-1.2
Data Power to Receiver	dBm	-120.0	-120.1	-120.1
Eb/No to receiver	dB	9.1	9.1	9.1
Systems Loss	dB	-1.5	-1.5	-1.5
Eb/No Output	dB	7.6	7.6	7.6
Threshold Eb/No	dB	4.6	4.6	4.6
Performance Margin	**dB**	**3.0**	**3.0**	**3.0**

Table 1. Mars Relay Return Link Budget for UHF, S and X-Bands

Mars Telemetry Link Budget - Areostationary Satellite

		UHF Forward	UHF Return	X-Band Forward	X-Band Return
Mars Radius	**3398 km**				
Orbit Altitude	**17100 km**				
Elevation angle	**deg**	**30.0**	**30.0**	**30.0**	**30.0**
TRANSMITTER PARAMETERS					
Transmitter Power,	dBm	40.0	40.0	37.0	34.8
Transmitter Circuit Losses	dB	-1.0	-1.0	-1.5	-1.5
Antenna Gain	dBi	10.0	0.0	15.0	26.0
Axial Ratio	dB	100.0	100.0	100.0	100.0
Modulation Index	deg	60.0	60.0	60.0	90.0
LINK PARAMETERS					
Range	km	18586.7	18586.7	18586.7	18586.7
Link Frequency	MHz	437.1	401.5	7171.0	8425.0
Atmospheric Attenuation	dB	0.0	0.0	0.0	0.0
Space Losses	dB	-170.6	-169.9	-194.9	-196.3
RECEIVER PARAMETERS					
Sky temperature	K	240.0	240.0	240.0	240.0
Pointing angle (Rel. to Nadir)	deg	8.3	8.3	8.3	8.3
Antenna Gain	dBi	0.0	10.0	24.6	36.4
Axial Ratio	dB	2.0	2.0	1.5	1.5
Polarization Losses	dB	-0.5	-0.5	-0.2	-0.2
Receiver Feeder Losses	dB	-1.0	-1.0	-1.5	-1.5
Receiver Noise Figure	dB	3.0	3.0	3.0	3.0
System Noise Temperature	K	550.9	550.9	556.1	556.1
Noise Spectral Density	dBm/Hz	-171.2	-171.2	-171.1	-171.1
TOTAL POWER SUMMARY					
Received Power	dBm	-123.1	-122.4	-121.5	-102.4
Received Pt/No	dB-Hz	48.1	48.8	49.6	68.8
SUPRESSED CARRIER - COSTAS LOOP					
Loop Bandwidth	Hz	400.0	100.0	400.0	400.0
Carrier Power/Total Power		-6.0	-6.0	-6.0	
Received Carrier Power	dBm	-129.2	-128.4	-127.6	
	dB				-3.0
Carrier SNR in the Loop	dB	16.0	22.8	17.6	39.8
Required Carrier Loop SNR	dB	10.0	10.0	10.0	17.0
Loop SNR Margin	dB	6.0	12.8	7.6	22.8
DATA CHANNEL PERFORMANCES					
Data Symbol Rate	sps	4000	16000	16000	2000000
Data Bit Rate (1)	bps	2000	8000	8000	1000000
Data Power/Total Power	dB	-1.2	-1.2	-1.2	0.0
Data Power to Receiver	dBm	-124.4	-123.6	-122.8	-102.4
Eb/No to receiver	dB	13.8	8.5	9.3	8.8
Systems Loss	dB	-1.5	-1.5	-1.5	-1.5
Eb/No Output	dB	12.3	7.0	7.8	7.3
Threshold Eb/No	dB	4.6	4.6	4.6	4.6
Performance Margin	**dB**	**7.7**	**2.4**	**3.2**	**2.7**

Table 2: Mars UHF and X-Band Links to an Areostationary Satellite

	VHF (100-500MHz)	S-Band (2-4 GHz)	X-Band (10-12 GHz)	Ka-Band (30-38 GHz)
Ionosphere (absorption & scintillation)	0.5 dB	0.15 dB	0.1 dB	0.05 dB
Troposphere (scattering)	0 dB	0 dB	0 dB	negligible
Gaseous	0 dB	0 dB	< 0.5 dB	< 1.0 dB
Cloud	0 dB	0 dB	0.05 dB	0.1 dB
Rain	0 dB	0 dB	0 dB	0 dB
Fog	0 dB	0 dB	0 dB	0.1 dB
Aerosol (Haze)	0 dB	0 dB	0 dB	0.1 dB
Dust*	0 dB	0.3 dB	1.0 dB	3.0 dB
Total Vertical Losses	0.5 dB	0.45 dB	1.15 dB	3.35 dB

* Worst case

Table 3. Radio Wave Attenuation in the Mars Region for Various Frequency Bands

Frequency Band (MHz)	Active Sensor Type			
	SAR	Altimeter	Scatterometer	Precipitation Radar
430-440	(F)			
1215-1300	SIR-C, JERS-1			
3100-3300	ALMAZ	RA2 (F)		
5150-5250	RADARSAT-2 (F)	TOPEX-2 (F)		
5250-5350	RADARSAT, ASAR, ERS1/2, ENVISAT ASAR(F)	TOPEX	ERS1/2, NSCAT (F), METOP ASCAT (F)	
5350-5470	RADARSAT-2 (F)	TOPEX-2 (F)		
8550-8650	(P)	(P)	(P)	
9500-9800	X-SAR	(P)	(P)	
9975-10025				(P)
13250-13400		TOPEX	NSCAT, SEAWINDS	TRMM (F)
13400-13750		TOPEX, ERS1/2	NSCAT, SEAWINDS, ENVISAT RA-2 (F)	TRMM (F)
(P) denotes proposed systems, (F) denotes future systems				

Table 4. Frequency bands for active sensors operating in the Earth environment